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Parallel Operation
of
Synchronous Machines

Electrical Engineering

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PARALLEL OPERATION
OF
SYNCHRONOUS MACHINES

BY

MILTON KENT AKERS B. S.

THESIS

FOR

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IN

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF ELECTRICAL ENGINEER

Morgan Brooks.

HEAD OF DEPARTMENT OF ELECTRICAL ENGINEERING

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PARALLEL OPERATION OF SYNCHRONOUS MACHINES.

Milton Kent Akers.

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Introduction.

This thesis was intended as a description of a method of compelling the division of load between synchronous machines, rather than a complete discussion of the phenomena of parallel operation of such machines. In as far as the author knows this method is new.# The statements herein have all been carefully varified by experiment.

The author desires, first of all, to acknowledge his deep indebtedness to Professor Morgan Brooks, with whom he has been associated in all his work on synchronizing and parallel operation. Afterwards, he wishes to acknowledge his indebtedness to Mr. J. M. Bryant and to Mr. F. G. Willson who have so materially assisted him, both with valuable suggestions and in the experiments that were performed. He wishes also to acknowledge indebtedness to the other members of the Electrical Engineering faculty and to the seniors in Electrical Engineering, who have materially assisted him in his work.

In connection with Professor Morgan Brooks, patent applications on this method have been made in the United States and in foreign countries.

According to Dr. Steinmetz the principal conditions of satisfactory parallel operation of synchronous machines are; first; equality of frequency; second, constancy of frequency; and third, equality of voltage. There are many other conditions that effect the operation of synchronous machines in parallel but of less importance.

Equality of Frequency.

Equality of frequency is taken to mean that the machines must operate together at the same frequency without excessive strains, either mechanical or electrical, upon them. Unless this condition exists, the machines can never be made to operate satisfactorily together. The condition of in-equality of frequency is that which occurs when two machines are belted to the same line shaft with pulley ratios such that the frequencies can never be the same. If two such machines are connected in parallel a current will flow between them. This current is a load current, and will load the machine of higher frequency to such a point as to supply sufficient power to cause the belts to slip; or the motor action on the machine of lower frequency will become so great that it will not hold in step, but will periodically fall in and out of step as the vectors come together and again separate. Any such operation is, evidently, out of the question.

Under the head of equality of frequency, rigid mechanical connection should be considered. Dr. Steinmetz says that this cannot be regarded as parallel operation and is not to be desired. This is true because any difference of position of the armatures on the shaft, or inequality of voltage cannot be taken care of

without a heavy circulating current, since there can be no change in the phase relation of the vectors. Later a method will be shown by the aid of which such operation may be made not only satisfactory, but in many cases desirable.

Constancy of Frequency.

Constancy of frequency is taken to mean that the frequency should be fixed, that is, that it should not vary. The ordinary variation of frequency due to regulation of the prime mover need not cause any difficulty. A condition, however, that may cause great trouble is best illustrated by an example. Consider two simple reciprocating engines each directly connected to a synchronous machine and the machines connected in parallel. Assume first that the machines are synchronised at such a position that the cranks of the engines are at ninety degrees. Since the load which each machine takes is at any instant in proportion to the torque, each machine, as the crank of its engine comes into the position of maximum torque, will take more than its share of the load. The result is that each machine will retain a definite portion of the load and the rest will change from one machine to the other, depending upon the instantaneous torque of each machine. The two machines will, consequently, not carry a load equal to the sum of the full loads of the two machines without each being, part of the time, overloaded. This condition of hunting may be cumulative and result in causing the machines to fall out of step. There is no such effect with machines that are steam or water turbine driven. Assume now, that the machines instead of being synchronized when the cranks were at ninety

degrees, were synchronized when they were together. Under these conditions the engines will, if the machines have equal number of poles, remain together, and both will come into the positions of maximum and minimum torque at the same time, and hence will periodically speed up and slow down. Such a variation of frequency would cause no serious trouble provided only lights and induction motors were to be operated on the system. There would, however, be trouble if synchronous motors and particularly synchronous converters were to be operated from them.

Equality of Voltage.

Equality of voltage is an essential element provided synchronous machines are to be operated together without any circulating current. If machines are in parallel and the excitation cannot be adjusted so that they will have the same voltage a circulating current will flow. This current is nearly wattless and is leading with respect to the machine of lower excitation and lagging with respect to the other. The result is that it tendsto increase the excitation of the less excited one and to decrease that of the other, and the circulating current that will flow under any conditions of excitation will be such as to cause the machines to operate at the same terminal voltage. Hence for machines that are to be operate in parallel a certain amount of armature inductance is necessary, since otherwise, even with a moderate difference in excitation, the circulating current that would flow would be excessive, and furthermore since the synchronizing power depends upon the armature inductance, it is necessary that there should be some inductance in order to keep the machines

from falling out of step. Thus in designing synchronous machines it has been necessary to sacrifice regulation in order that the machines will operate successfully in parallel. The load balancing method,as will be explained later,employs a synchronizing coil that will hold the machines in step independent of the armature inductance,and since the transformer controls the circulating current,it follows that with this method it is possible to operate machines in parallel that have as little inductance, and hence as good regulation ,as it is possible to build.

Inequality of voltage and consequently a circulating current may occur at one condition of load even if the machines were operating together at some other load without a circulating current,due to a difference in characteristics of the machines. Consequently an operator can hardly ever be sure that his machines are operating under the best possible conditions. This is even more true since the circulating current,even if large,being at right angles to the load current,makes but small indication on the ammeter. The operator can only manipulate the field rheostat till the current output for the load is a minimum,and since the current vector that he is changing makes but small indication on the ammeter,the position of most satisfactory operation is impossible to determine with even reasonable degree of accuracy.

There are many other things that materially effect the operation of synchronous machines in parallel. Of these wave form is of considerable importance. When machines of different wave forms are operated in parallel there will practically always be a circulating current between them. Recently one of

the largest power stations in the country experienced a great amount of trouble due to this cause. The machines in the plant were star connected, three phase, with a grounded neutral; a new machine from the same manufacturers was placed in parallel with them and without any load on the machine, the current transformer in the neutral burned out. A frequency meter in the neutral showed that the current there was three times the frequency of the system. An analysis of the wave forms of the machines at once disclosed the cause of the trouble. The wave form of the older machines was that of a sine wave with a triple harmonic, and that of the new machine was the same sine wave and the same harmonic, but with the harmonic reversed. Thus the equations of the two pressure waves were;-

$$A = C \cos \theta + K \cos 3\theta$$

$$B = C \cos \theta - K \cos 3\theta$$

The result of connecting machines of such wave forms in parallel is that the machines are held closely in phase with respect to the fundamental, and the harmonic may be at a much greater phase relation to each other, and hence cause a circulating current. In the special case mentioned above the machines were held with respect to the fundamental and the harmonic was thus in opposition. The double voltage of the harmonic was thus short-circuited thru the resistance of the neutral and the sum of the impedances, from terminal to the neutral, of the machines. This caused such a large circulating current that the neutral had to be opened and finally the machine was re-wound.

The question of engine government is also of considerable

importance. Thus, if tw machines are operating together and one of the engines governs more closely than the other, the machine with the better governed engine will take more than its share of the load at full load and less than its share at light load. Consequently, altho the machines may divide the load equally at one condition of load, they may not, without attention, divide the load equally at some other condition. If there is a very great difference between the engine government, a short-circuit or sudden increase in the load may cause the the closer governed machine to fall out of step, or if there is any difference at all, it is liable to start the machines to hunting, since the increase in load will all tend to fall on the machine with the closer governed engine. There are several other things which effect the operation of synchronous machines in parallel but these are in general of only small consequence.

The Load-Balancing Method.

A method will now be shown by the aid of which the operation of synchronous machines in parallel is made much simpler, and by which, any number of machines may be made to automatically divide the load among them, in any predetermined ratio. This device consists of a simple auto-transformer connected between the open terminals of two synchronous machines, the other two terminals being connected together in the usual manner thus making one line terminal. The other line terminal is connected to some point on the transformer winding, such that the ratio of the turns on the two sides is the inverse ratio of the capacities of the machines with which it is to be used. Figure (1)

represents the method, the machines being shown by vectors. (In this thesis all figures and discussions will be as applied to single phase; the method for any number of phases is a simple extension of that shown.)

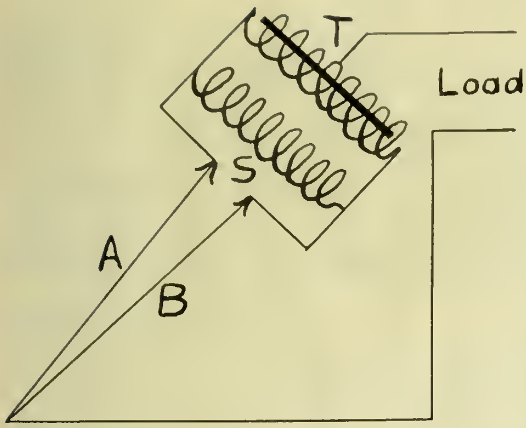

Figure I.

(A) is one machine (B) the other operating in parallel with it. (T) is the auto-transformer. The line terminal is shown connected to the middle point of the transformer; the point for equal load division by the two machines. Since the currents from the two machines flow in opposite directions thru the transformer to the line, the ampere turns on the two sides of the transformer are in opposition to each other. If now, the line connection to the transformer be placed, so that the ratio of the turns on the two sides, is the inverse ratio of the capacties of the two machines, when the machines are each furnishing a portion of the load in proportion to their capacties, the transformer will be non-inductive as to these load currents. For any circulating current the transformer is however very inductive, the currents being opposed by the full inductance of the transformer winding. This is then the fundamental principle of the load division method; a transformer so placed that the useful load currents meet no inpedance in opposition to their flow thru it, and yet so that any circulating current is opposed by the full inductance of the transformer; also a synchronizing coil that pulls the machines together when out of phase and holds them together when

in phase.

The effect of the load balancing method will now be considered from the stand point of each of the principle conditions of satisfactory parallel operation that have already been discussed.

Equality of Frequency.

As already explained inequality of frequency is an inoperative condition. The use, however, of the load-balancing method would prevent any injury to the machines if they should fall out of step.

As applied to machines that are rigidly connected the transformer is of great service. So much so that this method of operating machines may be made, not only staisfactory, but in many cases desirable. The difficulty in operating such machines is, as previously stated, due to the fact that any difference in the characteristics of the armatures, or in excitation, cannot be taken care of by phase adjustment, and consequently a large cross-current results. Figure (2) represents the condition that exists if the armatures of two machines that are operated mechanically connected, are not in their proper phase relation, and the machines unequally excited. The difference in phase position of the vectors represents the difference in phase position of the armatures on the shaft, and the difference in length represents the condition of unequal voltage. If these two machines were connected

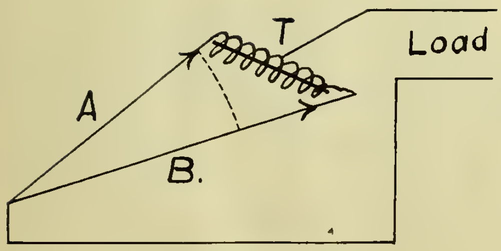

Figure 2.

in the usual manner, the cross-current that would flow would make it impossible to operate them together. If, however, the load-balancing transformer were connected between the terminals, as shown in the figure, and the middle point of the transformer taken as one terminal of the line, the circulating current would be opposed by the full inpedance of the transformer. On the other hand, the load currents of the machines would oppose each other and thus make the transformer non-inductive as to them. The voltage of the system would be the mean voltage of the two machines. The synchronizing coil is not necessary since the machines are held mechanically together.

Constancy of Frequency.

The best illustration of a condition of frequency not constant, is that known as hunting. Consider figure(3). When the condition of hunting exists the vectors representing the pressures of the machines cannot be placed in a fixed relation to each other, since they are constantly changing in phase relation. That is, figure (3) represents an instantaneous condition only. First the vector (A) then (B) will be ahead in phase. The load that each machine has is, at any instant, dependent upon its phase relation with respect to the other machine. Thus as each machine in turn moves ahear in phase, it takes more and more of the load till it is finally pulled back by the excess load, and if the condition

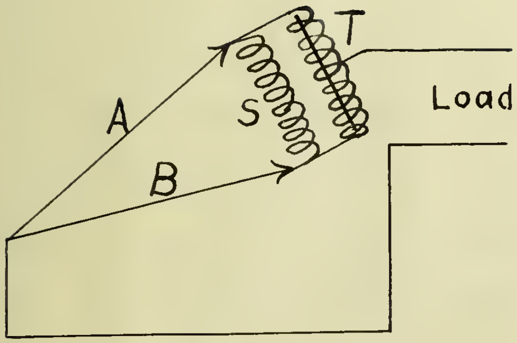

Figure 3.

is that of hunting, it will continue to fall behind till the other machine is ahead in phase and has the greater portion of the load. The load that a machine tends to take, when operating in parallel, is independent of its voltage but depends directly on its phase relation. The voltage at the terminals is a measure of the capacity that the machine has to take load. If the load-division method is used where such a condition of hunting exists it acts to eliminate it. The action of the method is as follows;- If a machine moves ahead in phase and thus tends to take more than its share of the load, the balance of the currents in the transformer is disturbed and the voltage of the machine is reduced. That is, as it tends to take more than its share of the load its capacity to take load is reduced and consequently it at once falls back in phase. In an experiment two synchronous converters, that operate together satisfactorily as alternating current generators, were paralleled as converters on the same direct current load. The load division transformers were put in the circuit and short-circuited, so that the machines were together in the usual manner. When they were paralleled under these conditions they would not hold in step long enough for the operator to open the short-circuiting switches. Several attempts were made but each time the machines fell out of step before the switches could be opened. Assistance was obtained, and the short-circuiting switches opened before the machines fell out of step. When this was done the machines continued to operate in parallel and to divide the load between them. The experiment was several times repeated and each time with the same result. This extreme case, tho not usual, shows well what the

method will do in cases of hunting.

Equality of Voltage.

The effect of unequal excitation on the machines is the same when they are operating independently in parallel as when they are rigidly connected. That is, the voltage of the system will be the mean voltage of the machines, and no cross-currents will flow. As previously stated, under normal conditions, the cross-current necessary to reduce the machines to the same voltage is limited by the armature reactions, and the greater the armature reactions the smaller will this cross-current be for a given difference in excitation. Since, with the load-balancing method in use, the cross-currents are limited by the transformer; it follows, that machines may, by its aid, be operated together that have such little armature inductance that they would not operate together with the usual method. It also follows that machines with much better regulation may be operated together, since the transformer effects the regulation only by its very small ohmic resistance.

The difficulty that the operator meets when he desires to change the pressure of the system, is also removed by the method. Heretofore when he has had to change the voltage of the system, it was necessary to change first one machine a small part of the desired increase and then the other, in order to avoid having a circulating current. With this method he can at once raise the first machine to the desired voltage, and then each in turn, without at any time having any considerable circulating current. This same effect may also be utilized if it happens that it is

impossible to excite all the machines to some particularly desired voltage, and some machines may have more margin in their rheostats and may be raised to a higher voltage than that desired, since the maximum voltage that can be obtained from each machine may be utilized, and without any serious circulating current.

The transformer is also very desirable where machines of different wave forms are to be operated in parallel. This applies to transformers as well as to generators. For example, in the particular case mentioned at the beginning of this thesis, had the load-balancing method been used, its impedance to the harmonic would have been three times the impedance of the winding because of the triple frequency, and at the same time it would have offered no impedance to the desirable load current. There are several ways in which it might have been installed. It might have been used in the manner shown in the figures in this thesis, or if it was desirable to keep at ground potential, it could have been used between the machines and the neutral, or even one transformer might have been placed in the neutral, and the ground connection taken off at the center. In this last position it would offer its impedance to the harmonic but would not oppose the necessary ground currents. In this position it would not have the other advantages mentioned.

It may also be used to good advantage where machines are driven by engines that have differences in government. The result of an experiment shows this very well. Two machines were put in parallel thru the load-balancing transformer. The machines were each made to take half of its full.load. The

field rheostat, of one of the driving motors, was then changed till the generator belted to the motor took the whole of the load. The field of the motor was then strengthened till the load all fell on the other machine, that is, making a change of from one hundred percent load to no load. The amount of change of the motor field that was necessary to effect this change of the load from one machine to the other, with the load-division transformer in such a position as to call for equal load currents, was noted. Then with the transformers short-circuited, so that the machines were together in the usual manner, the experiment was repeated. Under these latter conditions, with the same change in the motor rheostats as before, the machine changed from about one hundred fifty percent load to about fifty percent motor load. When the load-division method was in use, the load was not gradually transferred from one machine to the other, but each held its full share of the load up to the time of the change. The load then all fell at once on the machine with the greater driving torque. Thus for any usual difference in driving torque, the method will force the machines to each retain its share of the load. If a sudden load, falls on the system, it will not all fall on the machine with the closer regulated engine, but will fall equally on all the machines that are operating. It is not meant that the load-division method forces the engines to give out more power than is put into it; that is manifestly an impossibility. the transformer transfers the surplus of driving torque from the machine with too much to that with too little, just as in the limit the machine, with the small amount of driving torque, will become a motor receiving all its power thru the transformer.

So far explained, it has been assumed that sufficient synchronizing current would flow to hold the machines in phase. There is however a difficulty, one that as yet has not been mentioned. This is, that the load-balancing transformers, however arranged, if they are of sufficient size to have the desired effect, offer such a large impedance to the circulating current that the slightest inequality of driving torque causes the machines to fall a large amount out of phase in order to get sufficient voltage to force the necessary synchronizing current thru the transformers. This difficulty was, however, easily met and the solution added much to the method. To make the method operative it is necessary to add to the method as so far explained a synchronizing coil. This is the coil (S) in figure (1). This synchronizing coil readily carries the synchronizing current and in itself, by it inductance, acts to hold the machines together. With it, by experiment, it has been possible to force two machines together that would not stay together when the coil was short-circuited. It also filteres out the circulating current, and the operator, by a glance at the ammeter placed in series with it, can tell if the machines are operating at the best possible conditions. This, as already explained, as operating is normally, is almost an impossibility. The synchronizing coil should be without iron core, and may be used to synchronize the machines when they are to be placed in parallel.#

The method as a whole in the general form is shown in

Self-Synchronizing of Alternators, by Morgan Brooks and M.K.Akers. Milwaukee Convention of A.I.E.E., May 1906.

figure (4). The generators are here shown as single phase, the method, however, for any number of machines, for any number of phases, is a simple extension of the diagram shown. Where more than two machines are to be operated together the switching is simpler if an electric circuit be substituted for the magnetic one, as shown in the figure.

In the figure (Fig.4) 1,2,3,4, and 5 are the generators, represented as of different size, to be operated in parallel. On one side to the line there is only the switches S1,S2,S3,S4, and S5. The other terminals of the generators connect to the switches b1,b2,b3,b4, and b5. The auto-transformer $\overline{D1}'$ is shown connected across the terminals of the switch, as explained in the text. The load-balancing transformers are shown as D1,D2,D3 and D4. These transformers have all the same number of turns in the primary. The secondaries are connected in series and so as to short-circuit each other, the number of turns in each is proportional to the share of current that its primary is to carry. Since these secondaries are each short-circuited on the other, when each machine is carrying its share of the load the inductance for the load currents is negligible. The switches 1a,2a,3a, and 4a are for the purpose of short-circuiting the secondaries of the transformers when the machines are to be operated alone, or in the usual manner, on the system. The transformers $\overline{D1}'$ and D1 show how the auto-transformer may be used in combination with the other transformers, and serve to balance the load between two machines, the pair, in turn, being balanced with respect to the rest of the system. The coils E1,

E2,E3,E4,and E5 are the synchronizing coils. These are arranged to be left permanently on the system and are an absolute necessity to the operation of the method. Thses are shown as connected to the separate switches c1,c2,c3,c4,and c5,and to a separate bus,the synchronizing bus. Assume now that machines 1, 2, and 3 are running and it is desired to add machine 4 to the system. The situation is then as follows;- switches S1,S2,and S3; b1,b2,and b3; c1,c2,and c3; and 3a and 4a are closed; 1a and 2a are open. Now to put machine 4 on the system. It is first brought to speed and voltage,switch S2 is then closed, the synchroscope or phase lamp is placed between the synchronizing bus and the machine side of the switch b2. The synchroscope then shows the phase position of the machine,when correct synchronizing position occurs switch C3 is closed and the machines are at once forced into synchronism.# As soon as the machines are together the switch b4 is closed. The driving torque is then increased till the machine begins to assume part of the load. Switch 3a is then opened and the machine at once takes its share of the load on the system. The operator then adjusts the driving torque and the voltage till there is no current thru the synchronizing coil.

The capacity of the load-division transformers will depend upon the degree of closeness of division which is desired. The current capacity of the primary is the current capacity of the machine with which the transformer is to be used. The current capacity of the secondary is the same for all transformers in a single system,and is some predetermined value depending

See foot note page 15.

upon conditions. When it is desired that the switching should be on low voltage the current will be chosen large, but if it is desired to balance the load between stations, a separate system may be chosen with a voltage that may even reach transmission voltage, and consequently the voltage will be small.

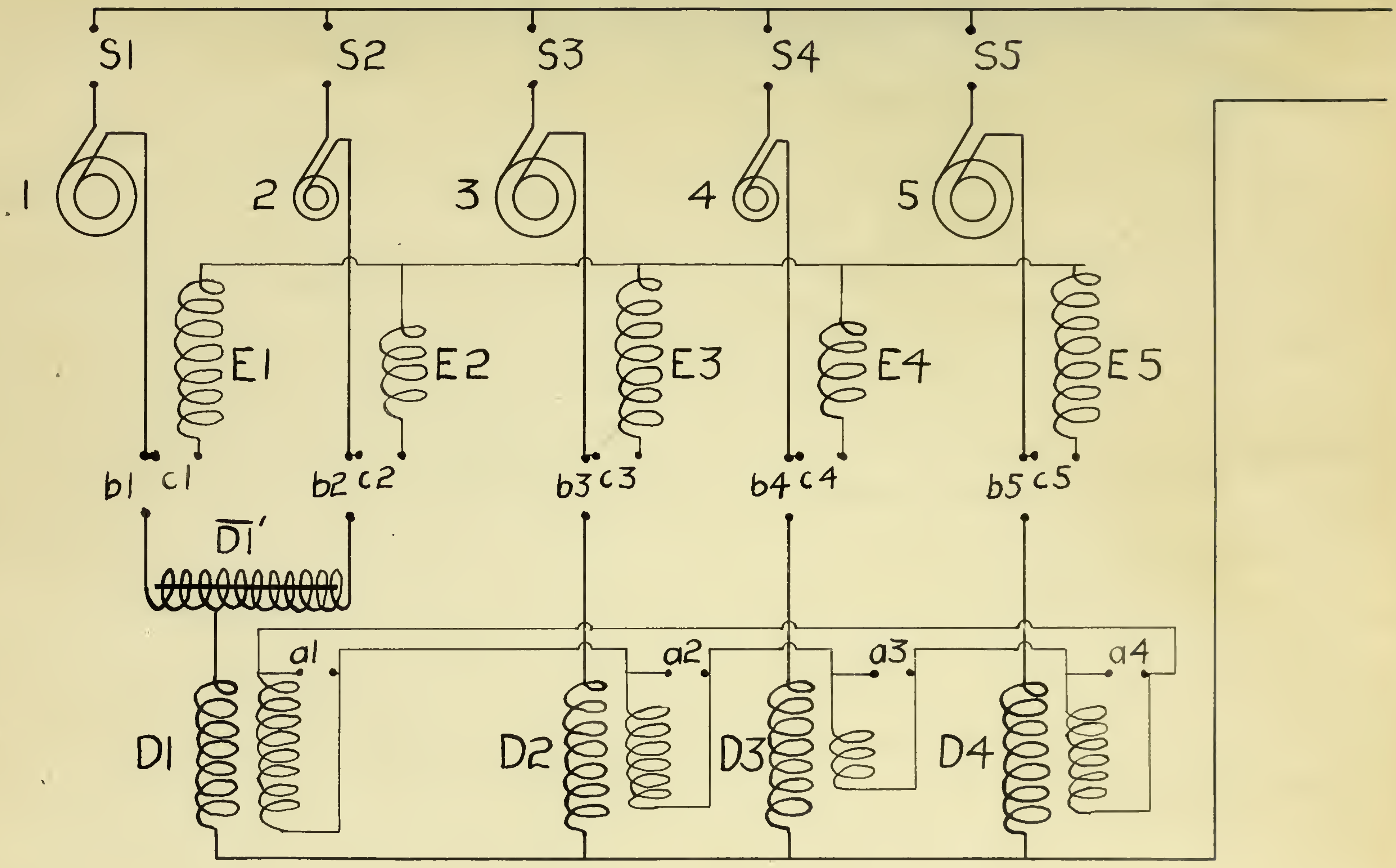
S1
S2
S3
S4
S5
1
2
3
4
5
E1
E2
E3
E4
E5
b1
c1
b2
c2
b3
c3
b4
c4
b5
c5
$\overline{D1}'$
a1
a2
a3
a4
D1
D2
D3
D4

Figure 4.